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MECHANICAL PROPERTIES OF 20% COLD-WORKED 316 STAINLESS STEEL IRRADIATED AT LOW DOSE RATE

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ABSTRACT

To assess the effects of long-term, low-dose-rate neutron exposure on mechanical strength and ductility, tensile properties were measured on irradiated 20% cold-worked Type 316 stainless steel. Samples were prepared from reactor core components retrieved from the EBR-II reactor following final shutdown. Sample locations were chosen to cover a dose range of 1-47 dpa at temperatures from 371-385°C and dose rates from 0.8-2.8 $\times 10^{-7}$ dpa/s. These dose rates are about one order of magnitude lower than those of typical EBR-II in-core experiments. Irradiation caused hardening, with the yield strength (YS) following approximately the same trend as the ultimate tensile strength (UTS). At higher dose, the difference between the UTS and YS decreases, suggesting the work-hardening capability of the material is decreasing with increasing dose. Both the uniform elongation and total elongation decrease up to the largest dose. Unlike the strength data, the ductility reduction showed no signs of saturating at 20 dpa. While the material retained respectable ductility at 20 dpa, the uniform and total elongation decreased to <1 and <3%, respectively, at 47 dpa. Fracture in the 30 dpa specimen is mainly ductile but with local regions of mixed-mode failure,

consisting of dimples and microvoids. The fracture surface of the higher-exposure 47 dpa specimen displays significantly more brittle features. The fracture consists of mainly small facets and slip bands that suggest channel fracture. The hardening in these low-dose-rate components differs from that measured in test samples irradiated in EBR-II at higher-dose-rate. The material irradiated at higher dose rate loses work hardening capacity faster than the lower dose rate material, although this effect could be due to compositional differences.

INTRODUCTION

The objective of this research was to evaluate the effects of long-term, low dose-rate neutron exposure on the tensile and fracture properties of 20% cold worked Type 316 stainless steel. The majority of information available on the effect of radiation on 20% cold-worked Type 316 stainless steel comes from experiments performed in the driver (fueled) regions of the EBR-II reactor where dose rates are on the order of $1x10^{-6}$ dpa/s (see Fig. 1). The material analyzed in this study came from 1-mm thick subassemblies (hex cans) irradiated in row 8 of the reflector region of EBR-II. The displacement rates in row 8 are about one order of magnitude lower than in the fueled region of the core. To examine the effect of dose rate on tensile properties, the results from this study are compared to the results of samples irradiated in row 2 of EBR-II and reported by Fish et al [1].

EXPERIMENT

Samples were taken from two different reflector hex cans removed from EBR-II upon final shutdown. These hex cans were identified as S1951 and S1952. Reflector S1951 was irradiated for 122,000 megawatt-days (MWD) in position 8D6 (row 8) in EBR-II. Reflector S1952 was irradiated for 9525 MWD in position 8A4 (row 8) in EBR-II.

Eight rectangular coupons were prepared by milling from the hex cans at selected locations. The coupons were then machined into test specimens using a traveling-wire electric discharge machine. The design of the tensile specimen conforms to both the ASTM-E8 and the Japan Industrial Standard (JIS) specifications for tensile testing. The overall specimen length is 60 mm, with a gauge length of 19 mm and a gauge width of 3.0 mm. The thickness of the specimens is 1.0 mm, corresponding to the thickness of the reflector hex cans.

The irradiation conditions for the samples are listed in Table 1. To form a direct comparison with a prior study [1] on

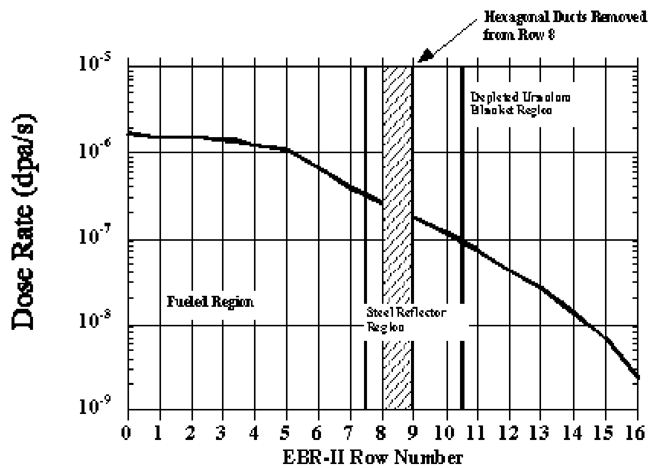

Fig. 1. Dose Rate as a function at EBR-II core axial midplane.

irradiated 20 % cold-worked Type 316 stainless steel irradiated at higher dose rate, the strain rate for the present tests was 4×10^{-5}/s, the same as the prior study. From the tensile tests, 0.2% offset yield strength, ultimate tensile strength, uniform elongation and total elongation were derived. Fractography was performed on specimens irradiated to 30 and 45 dpa to determine the effect of irradiation on fracture mode.

RESULTS

Table 1 summarizes the eight tensile tests. Fig. 2. displays the measured yield and ultimate tensile strengths as a function of dose. The data indicate hardening with irradiation, with the ultimate tensile strength reaching about 800 MPa near 20 dpa. Beyond that, hardening appears to be saturated. The yield strength also increases with increasing irradiation dose. The narrowing separation between the UTS and YS curves at higher dose suggests the work-hardening capability of the material is decreasing with increasing dose.

Ductility of the specimens as a function of dose is shown in Fig. 3. Consistent with the strength data, both the uniform elongation and total elongation decrease with dose. Unlike the strength data, however, ductility reduction showed no signs of abating at about 20 dpa. While the material retained respectable ductility at near 20 dpa, the uniform and total elongation decreased to <1 and 3%, respectively, at 47 dpa.

Table 1. Summary Engineering Tensile Properties(1) for the Eight Tests(2)

Speci-men	Damage (dpa)	Damage Rate ($x10^{-7}$ dpa/s)	Irrad Temp (°C)	YS (MPa)	UTS (Mpa)	UE (%)	TE (%)
S2T1	1		371	511	628	10.2	16.5
S2T2	1	0.76	371	473	597	12.0	15.4
S1T1	20	1.2	375	677	810	2.9	5.3
S1T2	20	1.2	375	680	824	3.5	6.6
S1T3	30	1.8	376	767	805	2.3	4.8
S1T4	30	1.8	376	676	805	2.3	5.1
S1T5	47	2.8	385	741	790	0.9	2.8
S1T6	47	2.8	385	770	787	0.5	1.9

(1) YS: 0.2% offset yield strength; UTS: ultimate tensile strength; UE: uniform elongation; and TE: total elongation.
(2) All tests were conducted at a strain rate of 4×10^{-5}/s at a temperature of 370°C.

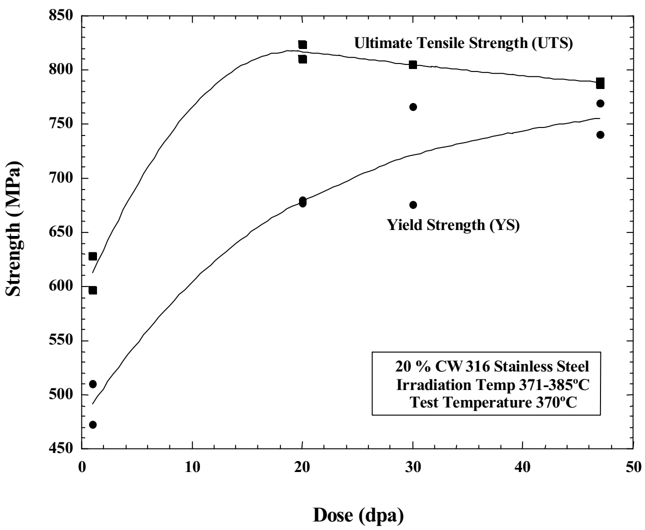

Fig. 2. Ultimate tensile strength (UTS) and 0.2% offset yield strength (YS) for 20% cold-worked Type-316 stainless steel hex can duct materials irradiated in EBR-II. The irradiation temperatures were from 371 to 385°C and the test temperature was 370°C. The strain rate was $4x10^{-5}$/s.

Posttest fractography was performed on two representative samples, S1T4 (30 dpa) and S1T5 (47 dpa) using a scanning electron microscope. Necking of the gauge section in the 30 dpa specimen is evident, but for the higher-dose S1T5 specimen, necking is almost imperceptible. This is consistent with the measured elongation data, which showed further reduction of ductility during irradiation from 30 to 47 dpa. Because necking constitutes a sizable fraction of the gauge deformation after the maximum load (uniform elongation) is attained before fracture, it reflects to a large extent the difference between the uniform and total elongation. In this respect, the differences of 2.8% for the 30-dpa S1T4 and 1.9% for the 47-dpa S1T5 appear to be consistent with the observed necking behavior.

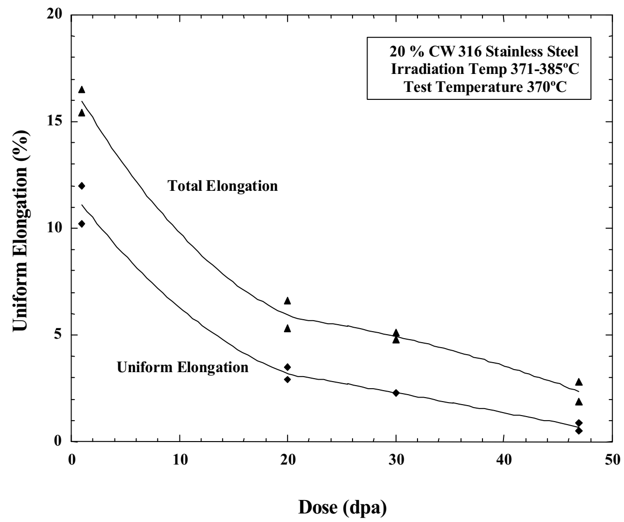

Fig. 3. Total and uniform elongations for 20% cold-worked Type-316 stainless steel hex can duct materials irradiated in EBR-II. The irradiation temperatures were from 371 to 385°C and the test temperature was 370°C. The strain rate was $4x10^{-5}$/s.

Fracture in the 30 dpa specimen is mainly ductile but with local regions of mixed-mode failure. The ductile fracture, illustrated in Fig. 4., consists mainly of dimples and microvoids. Among the dimples, there are faceted features that suggest flow localization and slip band decohesion. The 30 dpa sample has limited areas with mixed mode fracture (not shown) where some failure appears as a transgranular shear along active slip planes. The side surface of the S1T4 specimens shows steps from the tensile deformation; such features are typically associated with dislocation channeling or twinning in material.

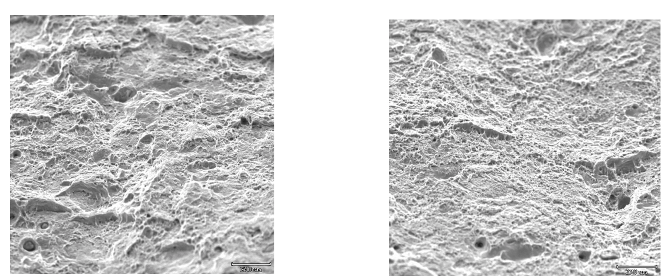

Fig. 4. Areas of fracture surface of S1T4 showing ductile dimples mixed with facets.

The fracture surface of the higher-exposure 47 dpa specimen displays significantly less ductile features, as shown in Fig. 5. The fracture consists of mainly small facets and slip bands that suggest channel fracture. Dimples and microvoids are far less abundant than in the lower-exposure S1T4 specimen. Noticeable steps are also found on the side surfaces of the specimens.

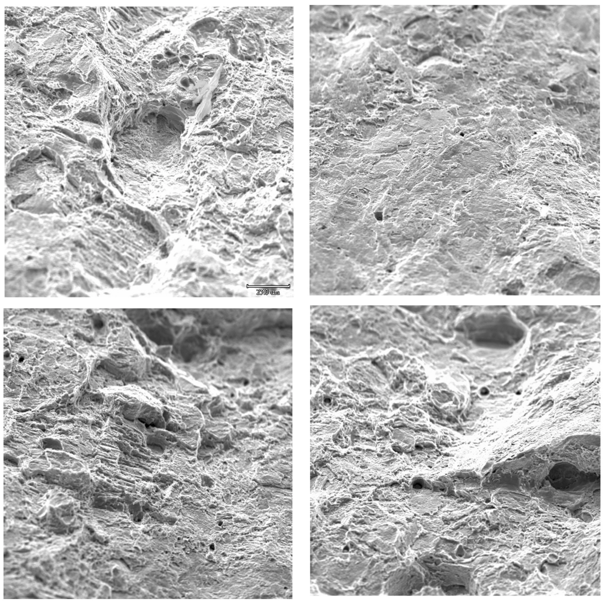

Fig. 5. Fracture of the S1T5 specimen showing channel faceted surface.

DISCUSSION

Few studies have attempted to determine the effect of dose rate on mechanical properties. Brager et al. examined the effect of displacement rate on tensile properties of annealed Type 316 stainless steel [2]. For samples irradiated from 371-424°C with a dose rate range of 0.8-8.4x10^{-7} dpa/s and tensile tested at 385°C, no effect of dose rate on yield strength was noted. For samples examined in the TEM, microstructural features were significantly different between samples irradiated at 1.0x10^{-7} and 8.4x10^{-7} dpa/s to 3.3 dpa. The higher dose rate samples had a larger precipitate density while the lower rate samples had a higher void density. In the same study, an effect of dose rate on yield strength was noted for Type 304 stainless steel. Brager concluded that the lack of effect of dose rate on yield strength of Type 316 was a “fortuitous situation in which a loss in strength contribution from precipitates as the displacement rate is decreased is offset by a concurrent gain in the strength contribution from the voids.”

A French study on solution annealed Type 316 stainless steel fuel cladding irradiated in the Rapsodie and Phenix reactors indicated that the saturation yield stress was greater in material irradiated in Phenix. The material irradiated in Phenix was irradiated at twice the dose rate of material irradiated in Rapsodie [3].

The tensile properties for the samples tested in this study can be compared to those of 20% CW Type 316 stainless steel irradiated in the high dose rate regions of EBR-II. Fish et al., measured the tensile properties of 20% CW Type 316 irradiated in row 2 of EBR-II [1, 4, 5]. The dose rate in row 2 is approximately one order of magnitude larger than that of row 8. To compare the two studies, the fluences reported by Fish were converted to doses using 1.5x10^{21} n/cm^2=1 dpa. This conversion is consistent with the dose/fluence calculations for the samples examined in this study.

The comparison of yield strength (Fig. 6.) indicates that, even though both sets of data come from nominally 20% cold-worked Type 316 stainless steel, the row 8 material has a yield strength at 1 dpa lower than the row 2 material at 1 dpa. The yield strength for both sets of data increases as a function of dose similarly beyond 1 dpa. The lower yield strength at 1 dpa in the row 8 samples could come from two possible sources. First, at the lower dose rate, a significant portion of the dislocation network may have annealed out between 0 and 1 dpa. At the low temperature of 370ºC, this annealing is not expected. Although the details of microstructural examination are not reported in this paper, the dislocation density of the row 8 material at 1 dpa is consistent with other studies of 20% cold-worked Type 316.

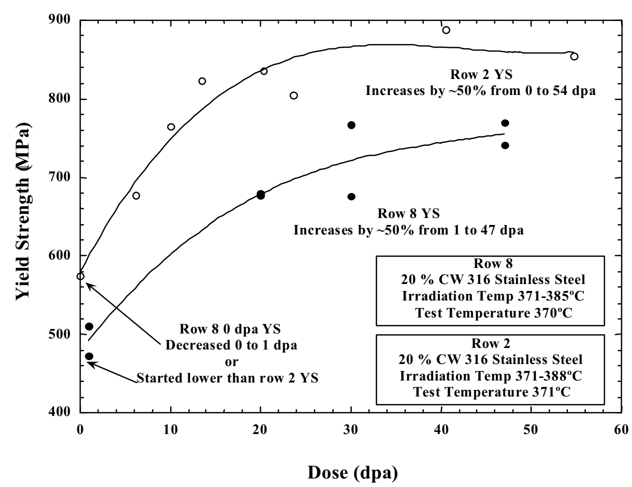

Fig. 6. Yield strength versus dose for samples irradiated in row 8 and row 2 EBR-II.

Alternately, the material irradiated in row 8 may have had lower yield and ultimate tensile strengths in the unirradiated state than the row 2 material. Because these ducts underwent standard quality assurance procedures prior to going into the reactor, the cold-work is not likely to differ significantly from the goal of 20%. On the o6ther hand, the ducts from this study and that of Fish came from different lots of steel and the compositional differences may have caused a difference in yield and ultimate tensile strength.

Table 2 compares the 1 dpa yield strength from three different experiments, the 20% cold-worked material irradiated in row 8 of EBR-II in this study, the 20% cold-worked material irradiated in row 2 of EBR-II in the Fish study, and 12% cold-worked material irradiated in row 9 of EBR-II [6]. The difference between the largest and smallest yield strength in Table 2 is about 80 MPa. Carson et al., measured the hardness at room temperature of Type 316 stainless steel as a function of cold-work [7] for various lots of material. For the material measured in Carson's study, the concentration of Cr varied from 16-18, Ni from 12-14, Fe from 64-69, and Mo from 2-3 wt%. For 12% cold-work, the room temperature hardness ranged from about 235-285 HV. Using the hardness-yield strength correlation developed by Higgy and Hammad [8], $\Delta\sigma_y=3.27\Delta H_v$ to convert the hardness data of Carson et al. to yield strength, the range of yield strength as a function of composition is about 164 MPa. At 20% cold-work, the range of hardness converts to a range in yield strength of about 195 MPa. The difference in yield strengths noted in Table 2 is bounded by the hardness measured by Carson. Because of the large variability of strength with composition, a direct comparison of yield strength as a function of dose of the row 2 and row 8 results cannot indicate if the irradiation dose rate has a significant effect on tensile properties.

Table 2. Effect of Cold work on Yield Strength

Cold-work/Irradiation Position	Yield Strength (370ºC) at low dpa (MPa)
12% Row 9	~580 (1 dpa)
20% Row 8	~500 (1 dpa)
20% Row 2	~575 (0 dpa)

The uniform elongation as a function of dose for the row 8 and row 2 samples is plotted in Fig. 7. No significant difference in the uniform elongation is noted between the two data sets.

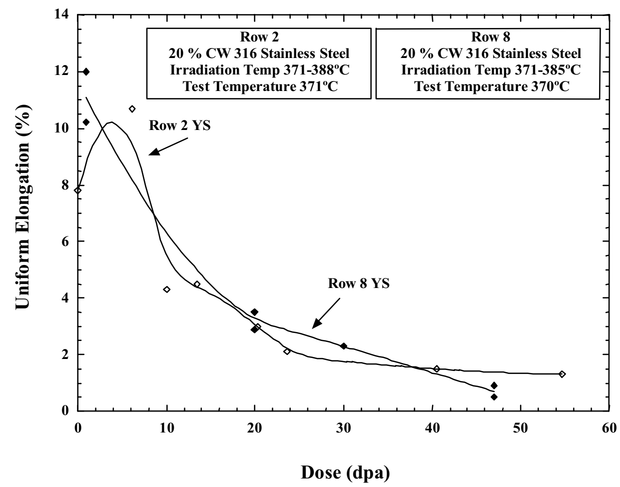

Fig. 7. Uniform elongation as a function of dose for samples irradiated in row 8 and row 2 of EBR-II.

Lucas [9] has noted the following relationship between uniform elongation, yield strength, and ultimate tensile strength:

$$\varepsilon_u = 0.5\left(1-\frac{\sigma_y}{\sigma_u}\right) \tag{1}$$

Figure 8. displays the hardening $\left(1-\frac{\sigma_y}{\sigma_u}\right)$ as a function of dose. The higher dose rate row 2 samples lose work hardening capability faster than the lower dose rate row 8 samples, even though there was no significant difference in the uniform elongation. Although no microstructural or fractography data is available from the Fish study, the loss of work hardening capacity may correspond with establishment of dislocation channeling as the primary deformation mechanism. If dislocations are free to travel through the material in slip bands, then less work hardening will occur.

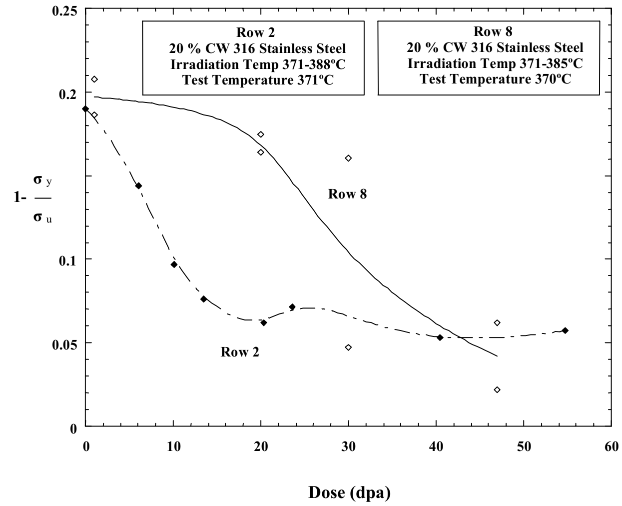

Fig. 8. Hardening as a function of dose. The higher dose rate row 2 samples lose work hardening capability faster.

The comparison of the strength and elongation of 20% cold-worked Type 316 stainless steel irradiated at different dose rates in EBR-II indicate the following:

- The row 8 samples have lower yield strength at 1 dpa than the row 2 samples. This difference is likely to be caused by compositional differences between the lots of Type 316 used in each study.
- No significant difference in uniform elongation is seen between the row 8 and row 2 samples.
- The higher dose rate row 2 samples lose work hardening capability faster than the lower dose rate row 8 samples. This may indicate that the deformation mode is dominated by dislocation channeling. This difference could be caused by either compositional differences or dose rate differences.

CONCLUSION

The comparison of the strength and elongation of 20% cold-worked Type 316 stainless steel irradiated at different dose rates in EBR-II indicates the following:

- The increases in strength of the row 8 and Row 2 samples follow a similar trend.
- No significant difference in uniform elongation is seen between the row 8 and row 2 samples.
- The higher dose rate row 2 samples lose work hardening capability faster than the lower dose rate row 8 samples.

The elongation and fractography data from the row 8 samples indicate that between 30 and 47 dpa, the fracture mode begins to transition from primarily ductile fracture to a fracture that is more channeled.

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